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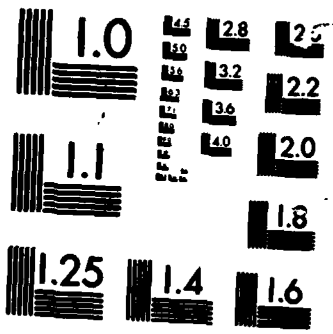

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Technical Report C86-04
March 1986

PRELIMINARY STUDY OF m_b BIAS AT SELECTED SOVIET SEISMIC STATIONS

Alan S. Ryall, Jr.

SPONSORED BY:
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Center for Seismic Studies
1300 N. 17th Street, Suite 1450
Arlington, Virginia 22209-3871
Telephone: (703) 276-7900

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Magnitude m_b was determined for five earthquakes on 25 and 27 May 1980, From recordings at eight Soviet seismic stations on a 4,300 km-long profile from eastern Kazakh to eastern Siberia. The records were hand-digitized, and magnitudes were determined from traces corrected for instrument response as well as the uncorrected traces. Four of the earthquakes were at Mammoth Lakes, California, in the western Great Basin; the fifth was at Tonga in the south Pacific. Magnitude residuals with respect to network-averaged m_b's listed in the ISC Bulletin were positive for stations at Yakutsk and Seymchan in Siberia, negative for raypaths through the Baikal rift zone, and slightly positive for a station at Semipalatinsk, about 100 km from the East Kazakh test site. A comparison of tabulated magnitude residuals for Soviet seismic stations from previous work of Ringdal (1985), North (1976) and Vanek et al. (1978, 1980) shows excellent agreement with previous work. Recalculation of m_b for 83 events recorded on granite at the Nevada Test Site provided a determination of magnitude bias (m_b = -0.10$\pm$0.35) for the NTS granite site with respect ISC magnitudes.

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22b. TELEPHONE (Include Area Code): (202) 694-3145

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Comparison of this value with m_b for the Soviet stations provides a direct measure of the NTS area relative to areas in the USSR in which the stations are located. This bias reflects only differences in attenuation, and does not account for differences in coupling, focusing, tectonic release, and instrumental effects. If focusing and instrumental effects are negligible, the magnitude bias due to attenuation differences between the NTS granite site and the station at Semipalatinsk is -0.20.

PRELIMINARY STUDY OF m_b BIAS AT SELECTED SOVIET SEISMIC STATIONS

by

Alan S. Ryall, Jr.

Abstract

Magnitude m_b was determined for five earthquakes on 25 and 27 May 1980, from recordings at eight Soviet seismic stations on a 4,300 km-long profile from eastern Kazakh to eastern Siberia. The records were hand-digitized, and magnitudes were determined from traces corrected for instrument response as well as the uncorrected traces. Four of the earthquakes were at Mammoth Lakes, California, in the western Great Basin; the fifth was at Tonga in the south Pacific. Magnitude residuals with respect to network-averaged m_b's listed in the ISC *Bulletin* were positive for stations at Yakutsk and Seymchan in Siberia, negative for raypaths through the Baikal rift zone, and slightly positive for a station at Semipalatinsk, about 100 km from the East Kazakh test site. A comparison of tabulated magnitude residuals for Soviet seismic stations from previous work of Ringdal (1985), North (1976) and Vanek *et al.* (1978, 1980) shows excellent agreement between these studies. Our results were slightly more scattered but in good agreement with previous work. Recalculation of m_b for 83 events recorded on granite at the Nevada Test Site provided a determination of magnitude bias ($\delta m_b = -0.10 \pm 0.35$) for the NTS granite site with respect to ISC magnitudes. Comparison of this value with δm_b for the Soviet stations provides a direct measure of the magnitude bias of the NTS area relative to areas in the USSR in which the stations are located. This bias reflects only differences in attenuation, and does not account for differences in coupling, focusing, tectonic release, and instrumental effects. If focusing and instrumental effects are negligible, the magnitude bias due to attenuation differences between the NTS granite site and the station at Semipalatinsk is -0.20.

Introduction

On 25 and 27 May 1980 three M_L 6+ earthquakes occurred in the western Great Basin near Mammoth Lakes, California, about 200 km NW of the Nevada Test Site. As part of our investigation of these earthquakes we requested seismograms from several seismic stations in the Soviet Union, including a station at Semipalatinsk, approximately 100 km NE of the eastern Kazakh test site. This note summarizes m_b determinations for five events on the Soviet records – the three large Mammoth Lakes events, a smaller (m_b 5.3) Mammoth Lakes shock, and an earthquake that occurred at Tonga (m_b 6.0) during the time frame of the recordings. The records were searched for eight more events on the ISC list, but none of these were recorded at the Semipalatinsk station and most were not recorded by the other stations. A moderate (m_b 5.4) Mammoth Lakes shock at 16:49

GMT on 25 May and an earthquake in the Kurile Islands (m_b 4.8) were recorded but not analyzed. Table 1 summarizes information on the events used in this study; the Kurile event is included for completeness.

Data

The data included recordings from eight seismic stations on a northeast-trending profile from Kzyl-Agach in the southern part of the Kazakh Fold System to Seymchan in the Northeast Siberian Fold System. Table 2 lists the station coordinates and Figure 1 is a polar projection of Asia showing the station locations. Table 3 gives epicentral distances and azimuths for the five events.

Figure 2 is a polar plot of the world centered on a point (81.5°N, 162.0°W) about halfway between the Mammoth Lakes earthquakes and station SEM, showing the epicenter and recording stations. Figure 3 shows the position of the Soviet stations on a lower-hemisphere, equal-area projection of the focal sphere for the three largest Mammoth Lakes earthquakes, together with projections of the fault and auxiliary planes for these events from a study of long-period P- and surface-waves (Given *et al.*, 1982). Based on point-source theory (Keilis-Borok, 1950) and the position of the stations on the focal

Table 1. List of Events

Date	Time, GMT	Latitude	Longitude	Depth	m_b	M_s
800525	16:33:44.7	37.596°N	118.830°W	6.5	6.1	6.1
800525	19:44:51.1	37.547°N	118.826°W	5.0	5.6	6.0
800525	20:35:48.5	37.616°N	118.847°W	6.1	5.3	5.7
800525	23:22:18.0	46.680°N	149.070°E	29	4.8	
800527	14:50:57.1	37.472°N	118.807°W	10.8	5.7	6.0
800527	13:01:37.9	18.610°S	174.700°E	55	6.0	4.8

Table 2. Station Locations

Code	Name	Coordinates	Region
BOD	Bodaibo	57°51'N, 114°11'E	Baikal
ELT	El'tsovka	53°15'N, 86°16'E	Altai-Sayan
IRK	Irkutsk	52°16'N,104° 19'E	Baikal
KZL	Kzyl-Agach	45°25'N, 78°45'E	Kazakhstan
SEI	Seymchan	62°53'N, 152°26'E	Northeast
SEM	Semipalatinsk	50°24'N, 80°15'E	Kazakhstan
UST	Ust'-Kan	50°57'N, 84°45'E	Altai-Sayan
YAK	Yakutsk	62°01'N, 129°43'E	Yakutiya

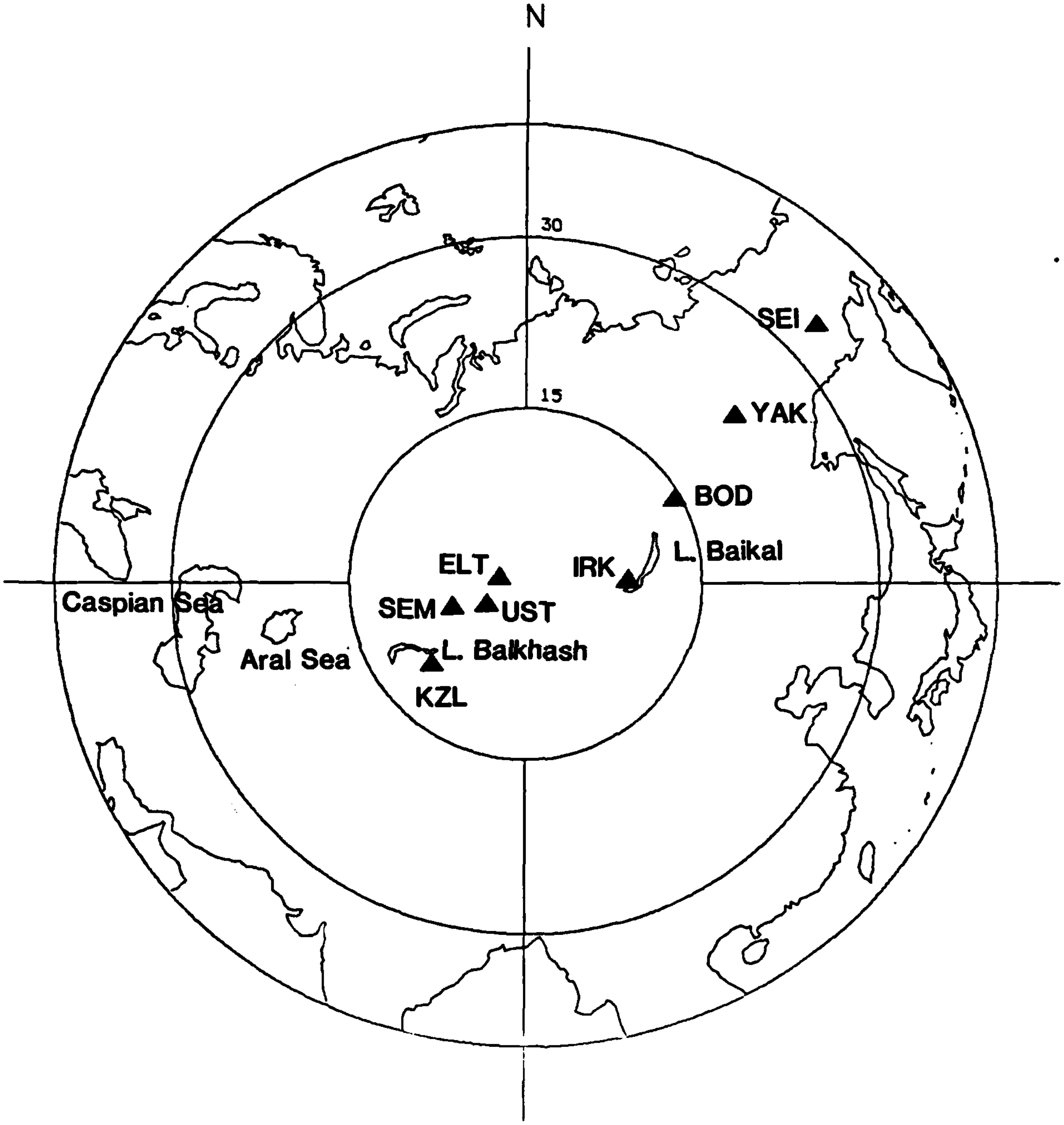

Figure 1. Polar projection of Eurasia showing stations used in this study. Radius of map is 40°.

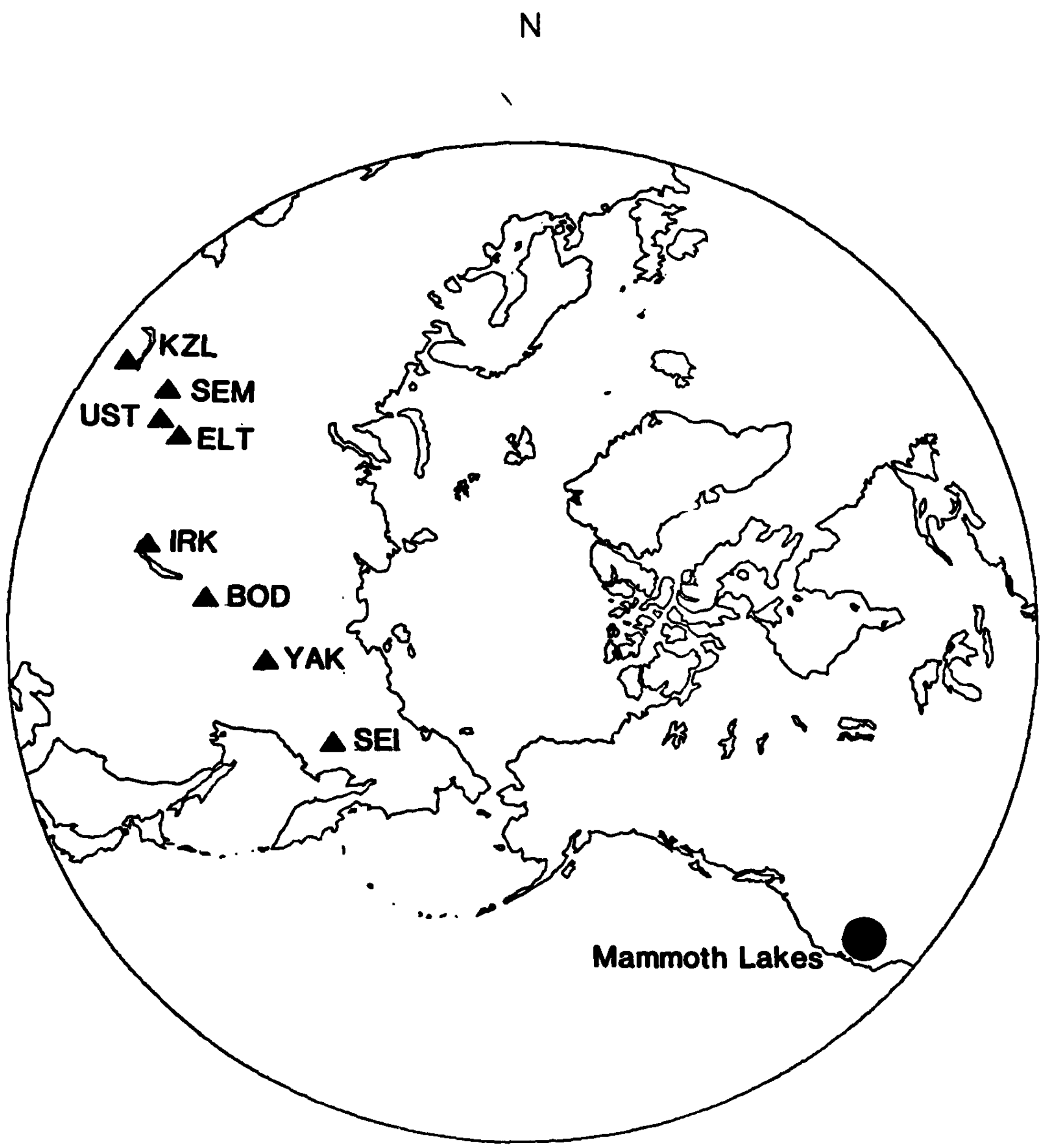

Figure 2. Polar projection showing location of Mammoth Lakes earthquakes (solid circle) and stations used in study (triangles). Radius of map is 52°.

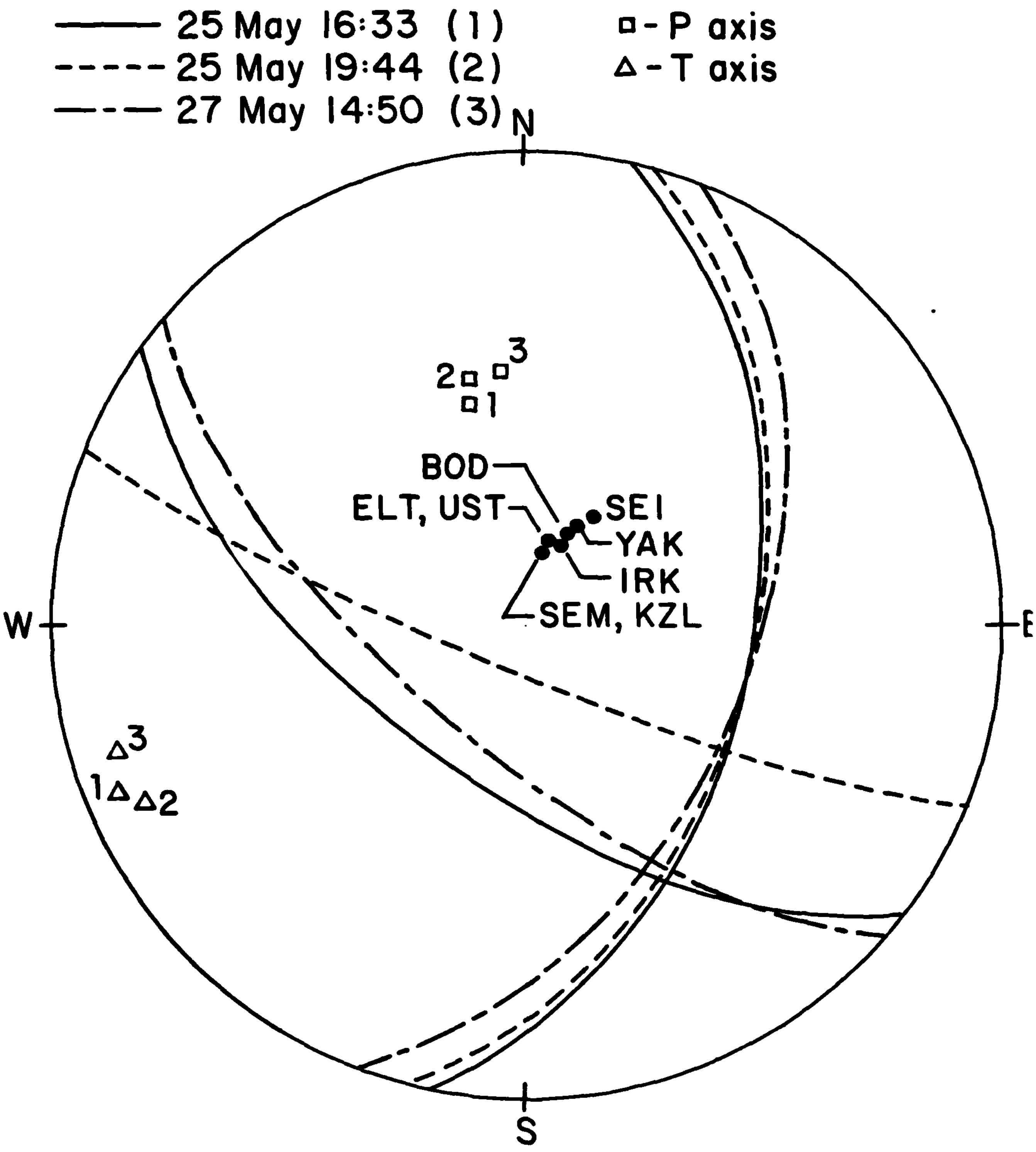

Figure 3. Fault-plane solutions for three of the largest Mammoth Lakes earthquakes (from Given *et al.*, 1982). Lower-hemisphere, equal-area projection. Solid circles -- location of raypath to Soviet stations used in study.

Table 3. Distance (Δ°) and Asimuth (Θ°) to the Stations												
Sta	05251633		05251944		05252035		05271450		05252322		05271301	
	Δ	Θ	Δ	Θ	Δ	Θ	Δ	Θ	Δ	Θ	Δ	Θ
BOD	75.09	334	75.14	334	75.07	334	75.21	334	23.81	311	95.95	329
ELT	86.95	345	86.99	345	86.92	345	87.07	345	39.76	303	110.06	321
IRK	82.93	335	82.98	335	82.91	335	83.05	335	29.24	298	99.15	322
KZL	95.86	348	95.91	348	95.84	348	95.99	348	47.30	296	114.54	312
SEI	56.77	327	56.82	327	56.75	327	56.89	327	16.35	6	85.23	346
SEM	90.78	348	90.83	348	90.76	348	90.91	348	44.24	301	113.66	318
UST	89.43	345	89.48	345	89.41	345	89.55	345	41.37	300	110.82	318
YAK	66.51	331	66.55	331	66.48	331	66.63	331	18.94	331	91.54	337

sphere, P-waves to the Soviet stations should have about 80% of the maximum radiated amplitude.

Figure 4 is a polar projection centered on a point (23.0°N, 147.0°E) about halfway between station SEM and the Tonga earthquake. The Kurile event (Figure 5) was in a poor distance range (16-47°) for this study, and and had large scatter in m_b values; it will not be considered in the detailed discussions that follow. For the Tonga earthquake a plot similar to Figure 3 indicates that the Soviet stations are close to the null axis on the fault-plane solution, although the latter is not well-constrained.

Table 4 lists instrument parameters for the 86 recordings that were supplied. Values of the maximum magnification V_m and the period range T_m (corresponding to $V = 0.9\ V_m$) were written on the records. For station KZL the period range T_m was not supplied and the range given in the table was taken from the Soviet earthquake bulletin (Akademiya Nauk SSSR, 1983). For station BOD the values of V_m marked on the recordings -- "2900" for the NS component and "2700" for the Z and EW -- appeared to be an order of magnitude too low, and the magnification (52,000) for that station was also taken from the earthquake bulletin. Use of the larger magnification for BOD is supported by Shishkevish (1974), who lists V_m as 45,000-49,000 for this station in 1970.

For this study only vertical-component recordings from SKM-3 seismographs were used. The SKM-3 system consists of a seismometer and galvanometer with instrument constants designed to produce magnification of ground motion in the range 30,000-100,000 over the period range 0.3-1.5 seconds. Appendix A contains a description of the SKM-3 system, equations for calculating the relative amplitude response and phase shift as a function of period, and instrument response calculations for the eight stations from which recordings were obtained. Figure 6 shows relative amplitude response for the eight

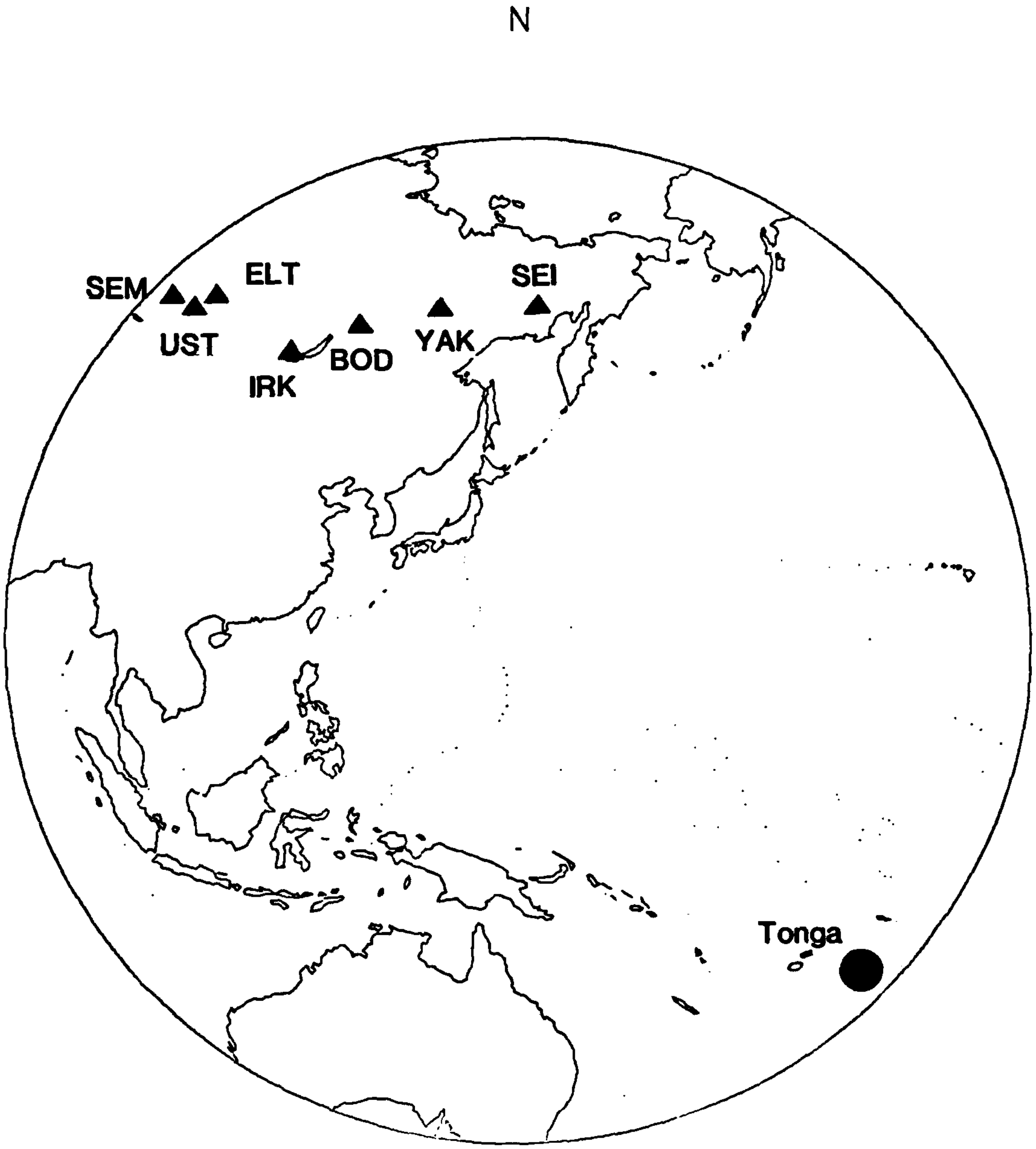

Figure 4. Polar projection showing location of Tonga earthquake (solid circle) and stations used in study (triangles). Radius of map is 60°.

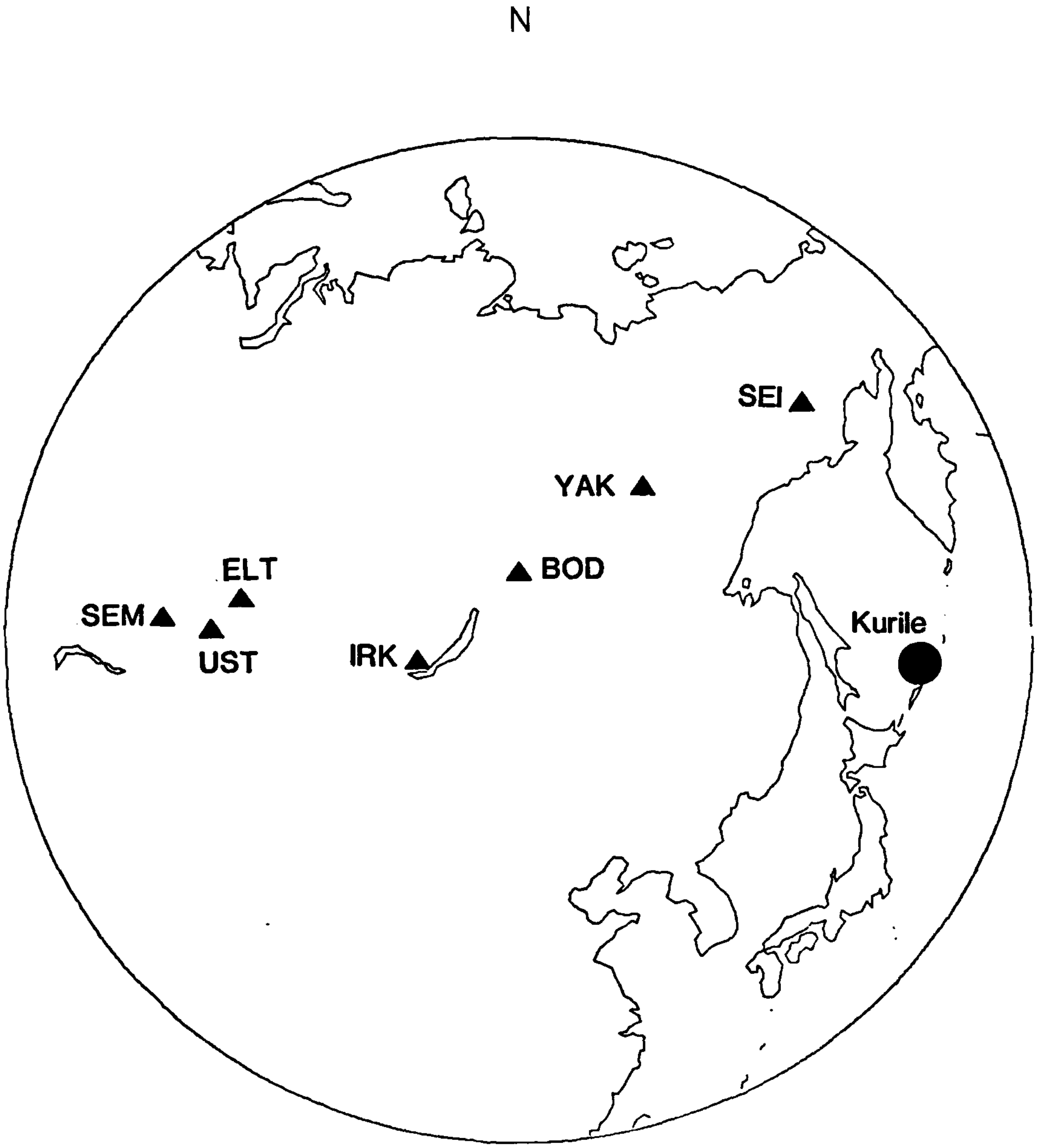

Figure 5. Polar projection showing location of Kurile earthquake (solid circle) and stations used in study (triangles). Radius of map is 30°.

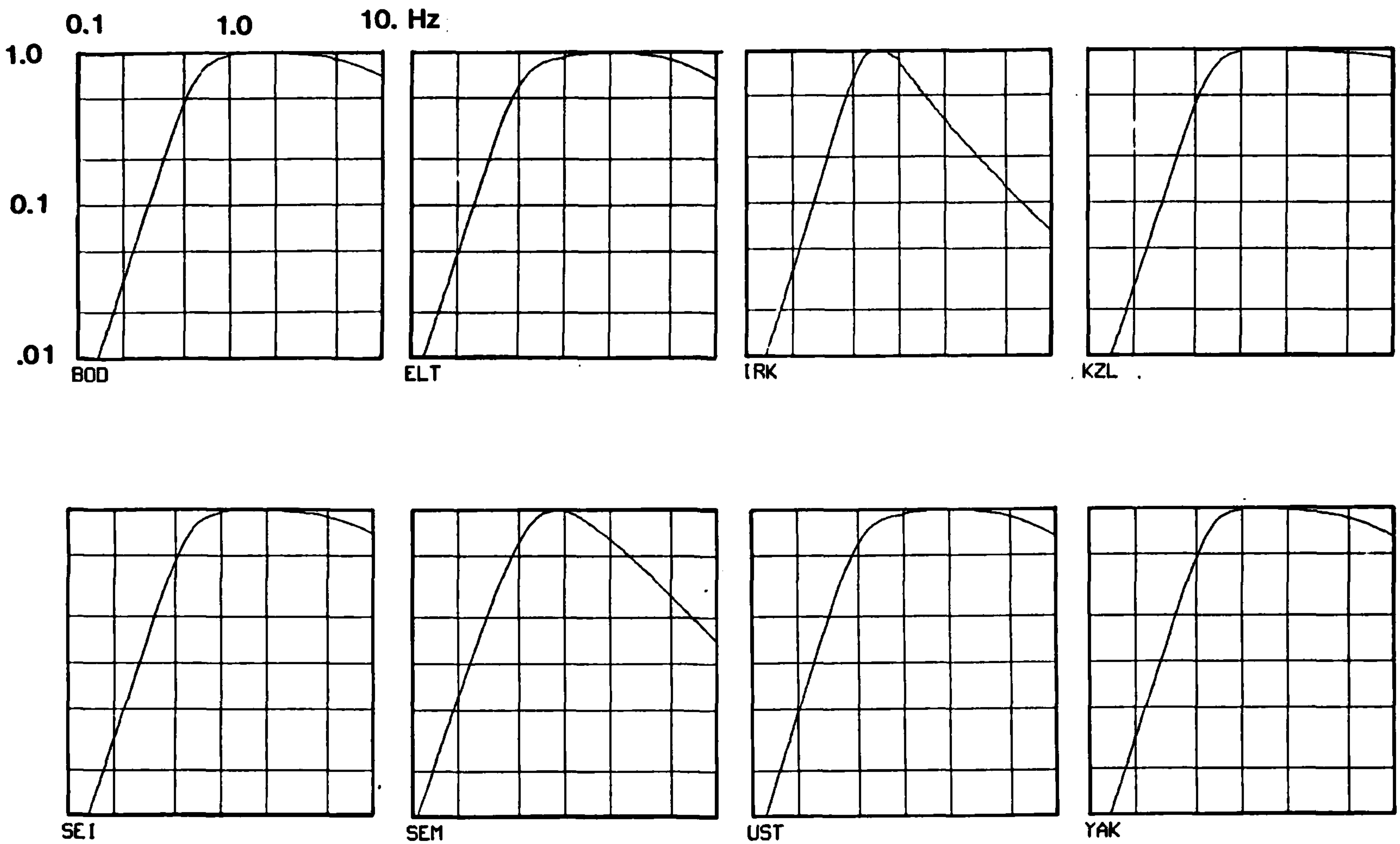

Figure 6. Response curves for SVK-M3 short-period vertical instruments for stations used in this study.

Table 4. Data Received for 25 and 27 May 1980				
Sta	Inst	Comp	V_m	T_m
BOD	SKM-3	NS,Z,EW	52,000	0.2 - 1.2
ELT	SKM-3	NS,Z,EW	50,000	0.2 - 1.4
	SKM-3	EW	5,000	0.2 - 1.4
IRK	SKM-3	NS	17,500	1.1 - 1.6
	SKM-3	Z	17,240	1.1 - 1.6
	SKM-3	EW	17,430	1.1 - 1.6
	SKD	NS,Z,EW	1,200	0.2 - 20
KZL	SKM-3	NS	40,900	0.08 - 1.6
	SKM-3	Z	41,500	0.08 - 1.6
	SKM-3	EW	40,600	0.08 - 1.6
	SKM-3	EW	1,050	0.08 - 1.2
SEI	SKM-3	NS,Z,EW	44,600	0.2 - 1.2
	SKD	NS,Z,EW	1,050	0.2 - 20
SEM	SKM-3	NS,EW	30,050	0.84 - 1.5
	SKM-3	Z	28,400	0.8 - 1.5
	SK	NS,EW	1,700	0.41 - 10.9
	SK	Z	1,100	0.5 - 11
UST	SKM-3	NS,Z,EW	50,000	0.2 - 1.4
	SKM-3	E-W	5,000	0.2 - 1.4
	SKD	NS,Z,EW	1,000	0.2 - 22
YAK	SKM-3	Z	18,800	0.3 - 1.3
	SKM-3	NS	37,600	0.8 - 1.4
	SKM-3	EW	36,800	0.8 - 1.4
	SK-KPCh	NS	140	0.3 - 11
	SK	NS	2,130	0.4 - 11
	SK	Z	680	0.4 - 9.0
	SK	EW	1,930	0.4 - 11

stations, determined from equations given by Aranovich *et al.* (1974). The Soviet short-period seismographs peak at lower frequency (*ca.* 1 Hz) than systems commonly used in the US, and for some stations (*i.e.*, SEM and IRK in this study) the system gain is down by about a factor of ten at 10 Hz.

Table 5 lists the time period covered by each of the recordings. Except for the SKM recordings at station KZL and the long-period recordings at UST all of the records were 12 hours long. The KZL record has twice the time resolution of the other short-period stations and appears to be changed three times daily; the SKD record for UST for 25 May was 24 hours long. Unfortunately the records of primary interest to this analysis -- from station SEM -- were changed at different times than those at other stations and overlap with the latter for only two six-hour periods.

Table 5. Periods Covered by Recordings									
Sta	Instrument	Time on		Time off		Time on		Time off	
		Date	Time	Date	Time	Date	Time	Date	Time
BOD	SKM-3	25	1206	26	0002	27	1205	28	0002
ELT	SKM	25	1205	26	0001	27	1204	28	0001
IRK	SKM3,SKD	25	1207	26	0018	27	1207	28	0009
K-A	SKM	25	0904	25	1700	27	0903	27	1650
SEI	SKM3,SKD	25	1002	25	2200	27	1002	27	2200
SEM	SKM3,SK	25	1628	26	0401	27	0418	27	1601
U-K	SKM3	25	1208	26	0005	27	1155	28	0005
	SKD	25	0010	26	0005	27	1155	28	0005
YAK	SKM3,SK	25	1203	26	0003	27	1205	28	0001

Record Quality. Copies of the records were on 35 mm film of poor-to-good quality. For many of the short-period records the contrast between the trace and the background was poor, and attempts to make enlargements of the waveforms using a reader-printer were not successful. As a result the records had to be projected on a viewing screen and traced by hand; the tracings were then digitized for computer analysis. Quality of the KZL records was especially poor, and the P-waveform for only one event was traced for that station.

Timing. Two or three time corrections were marked on each of the records, usually corresponding to the beginning and end of the recording period. Clock corrections changed at most stations by less than a second per day. A few records were mislabeled as to sense of the time correction, and in one case the time corrections at the two ends of a recording period were interchanged on different records of the same station. The largest clock drift was 0.5 second/hour for the SEM station, but this rate was constant. Tracings of the P-waves were made from enlarged projections of the film, with average time scale about 270 mm/minute. Station KZL had a drum speed twice that of the other stations, so the enlarged traces were viewed at a scale of 540 mm/min. For most of the events the beginning of the P-wave (PKP for stations at $\Delta \geqslant 110^\circ$) was identified on records of one of the better stations (SEI, YAK, BOD) and the same point was marked and timed on traces for the other stations by overlaying the recordings.

Traveltime residuals were calculated for the Mammoth Lakes earthquakes using hypocentral coordinates and origin times determined by the University of Nevada from recordings of a dense local network, and traveltimes calculated from the Herrin *et al.* (1968) tables. Initially, expected arrival times were calculated using the *PRED.arr* at the Center for Seismic Studies; however, this program calculates times from the Jeffreys-Bullen (1940) traveltime tables, which differ by more than three seconds from those of Herrin *et al.* over the distance range of interest. This resulted in unreasonably large

negative residuals for most of the Soviet stations. The Herrin *et al.* tables produced a pattern of residuals that was more reasonable in terms of known crustal structure at the stations and complex rupturing in the Mammoth Lakes sequence.

The Soviet stations had average delays of 0.5-2.2 seconds for the Mammoth Lakes events, relative to the Herrin tables (Table 6). These delays are not considered to be meaningful for the present study, since the larger earthquakes of this sequence appear to have been multiple events, initiated by small ruptures that recorded at regional stations but not at teleseismic distance ranges (Given *et al.*, 1982; Lide and Ryall, 1984; Wallace, 1985). On the other hand, traveltime residuals for individual stations relative to the average delays for all the stations (Table 7) are fairly consistent for the Mammoth Lakes and Tonga earthquakes. Note that the two stations north of Lake Baikal (BOD, IRK) have early arrivals for waves travelling southwest across the Siberian platform from the Mammoth Lakes events, but are late for paths from Tonga that cross the Baikal graben. Residuals for station SEM are small, and their average is almost zero.

Table 6. Total P-Wave Arrival-Time Residuals, Seconds

Sta	251633	251944	252035	271450	271301
BOD	-0.4	+0.2	+0.4	+1.4	+0.5
ELT				+1.2	-2.4
IRK	-0.1	-0.4	+1.3	+1.3	-0.8
KZL	+0.6				
SEI	+1.4	+1.0	+2.2	+3.6	-0.1
SEM	+1.3	+1.3	+2.7	+2.4	-0.4
UST	+1.1	0.0	+1.4	+2.7	-1.5
YAK	+0.6	+1.1	+1.5	+2.8	-1.3
AVG	+0.6	+0.5	+1.6	+2.2	-1.0

Table 7. Relative P-wave Residuals, Seconds

Sta	251633	251944	252035	271450	271301	Average
BOD	-1.0	-0.3	-1.2	-0.8	+0.5	-0.6±0.7
ELT				-1.0	-1.5	-1.3±0.4
IRK	-0.7	-0.9	-0.3	-0.9	+0.2	-0.5±0.5
KZL	0.0					0.0
SEI	+0.8	+0.5	+0.6	+1.4	+0.8	+0.8±0.3
SEM	+0.5	-0.5	-0.2	+0.5	+0.5	+0.2±0.5
UST	+0.5	-0.5	-0.2	+0.5	-0.7	-0.1±0.6
YAK	0.0	+0.6	-0.1	+0.6	-0.0	+0.2±0.4

Magnitude Determination

Figures 7-12 show the digitized P-waves for the Mammoth Lakes, Tonga and Kurile earthquakes (latter included for completeness but not analyzed). All traces are from SVK-M3 instruments, and are normalized; up on the traces corresponds to ground motion up. With the exception of KZL most of the recordings had good signal-to-noise ratio for the large Mammoth Lakes and Tonga events. For the first (1633Z) Mammoth Lakes earthquake, stations YAK and BOD appear to have higher frequency content than some of the other stations, including SEM (Figure 7), but this could be due in part to differences in instrument response. P-wave spectra for this event, corrected for instrument response, have peaks at about 0.5 and 0.7 Hz; for station BOD the peaks are about equal in amplitude, but for the other stations the amplitude at 0.7 Hz is less than half that at 0.5 Hz. For the first Mammoth Lakes (1633Z) event the character of the P-wave at the various stations is similar, consisting of a small first arrival followed 6 seconds later by a larger phase. The time interval between these phases is too consistent for the second arrival to be PcP, since for the distance range of the Soviet stations t(PcP-P) should vary from 60 seconds to zero. The second phase could be another earthquake, but this is unlikely because all of the Mammoth Lakes events have a large second arrival at the Soviet stations. A more likely explanation is that the phase includes the reflected waves pP and and sP. Based on the known crustal structure in the Mammoth Lakes area, a pP-P time of 6 seconds would be consistent with focal depth of about 16 km, and for that depth the sP-P time would be about 8 seconds. For the second and third Mammoth Lakes earthquakes in Table 1, the later phase follows P by 4.9 and 2.5 seconds, respectively; if this phase was pP the times would be consistent with focal depths of about 13 and 6.5 km. The fourth Mammoth Lakes event has a complex P-signature, and timing of the second phase is not consistent from one station to another.

Magnitude was determined from computer plots of the digitized P-waves using the standard formula

$$m_b = \log_{10} \frac{A}{T} + B(\Delta),$$

where A is the amplitude of vertical ground motion in nanometers and T is the period corresponding to amplitude A. The range in m_b values listed in the *Bulletin of the International Seismological Centre* suggests that some observatories measured the amplitude of the initial P-wave for the Mammoth Lakes events, while others measured the amplitude of the second phase. The IASPEI Commission on Practice Concerning Amplitude and Period Measurement recommended in 1979 that "the P wave amplitude measured should be that of the maximum trace deflection, usually within the first 25 seconds of the first onset or before the arrival of the next clear phase." Other workers have recommended measuring A and T within the first few cycles (Zavadil, 1980) or even within the first 3/4 cycle (the "b" amplitude) of the P-wave (Eisenhauer, 1980). Because of the discrepency

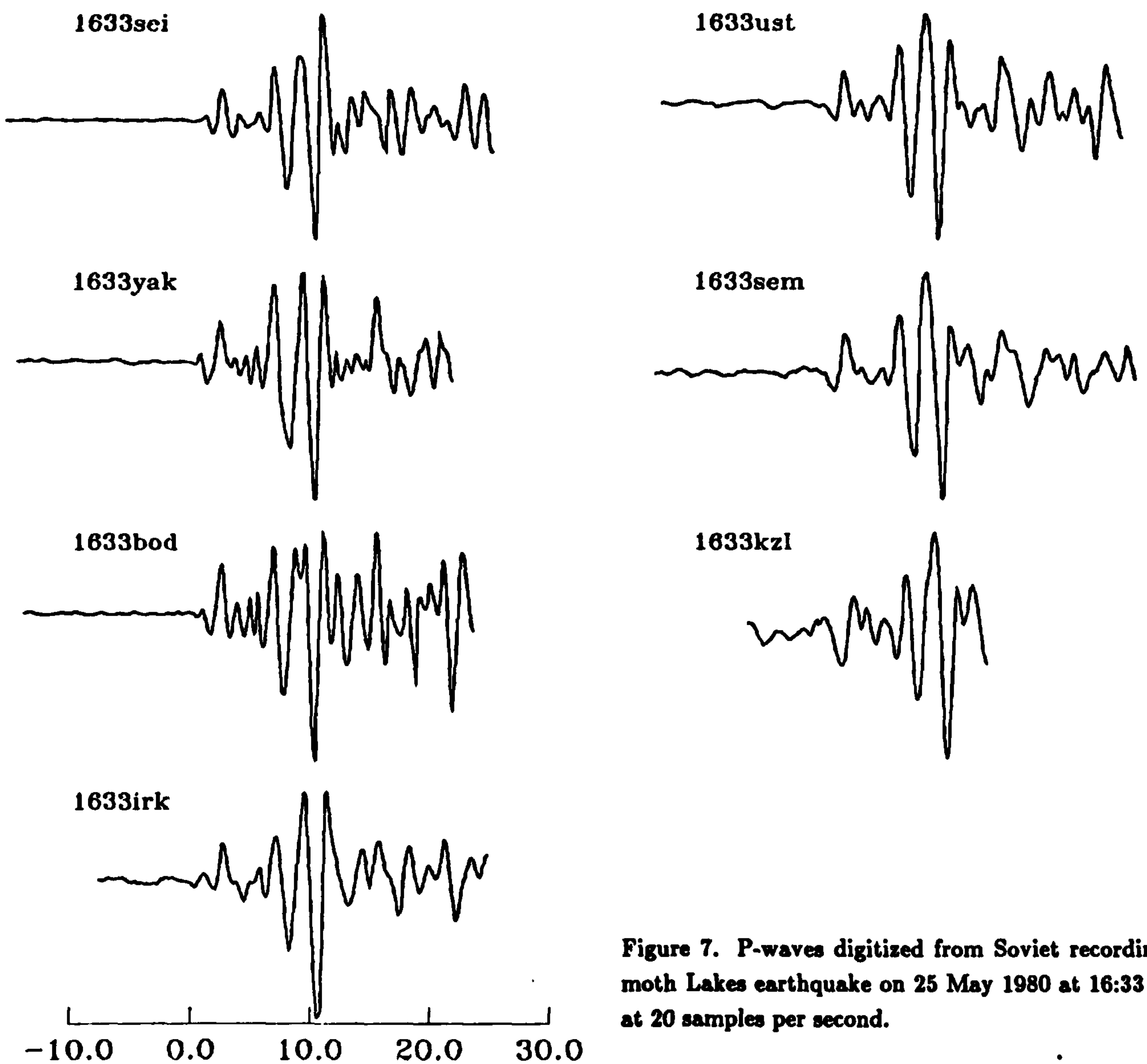

Figure 7. P-waves digitized from Soviet recordings for the Mammoth Lakes earthquake on 25 May 1980 at 16:33 GMT, resampled at 20 samples per second.

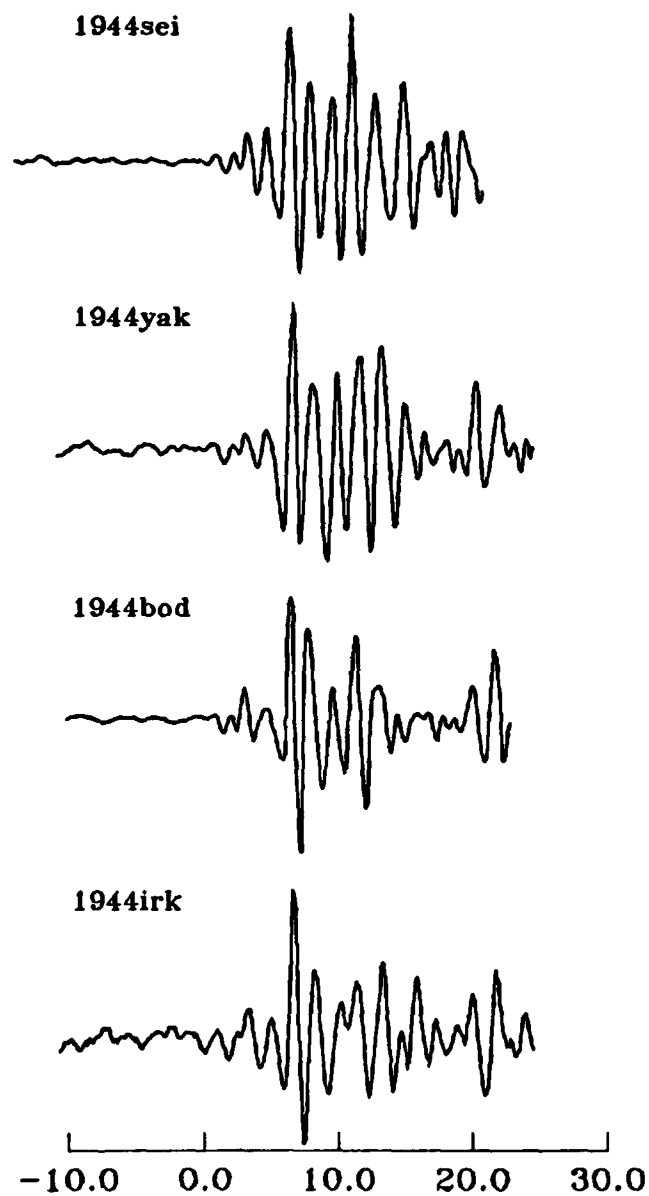

Figure 8. Digitized P-waves for Mammoth Lakes event at 19:44 GMT on 25 May.

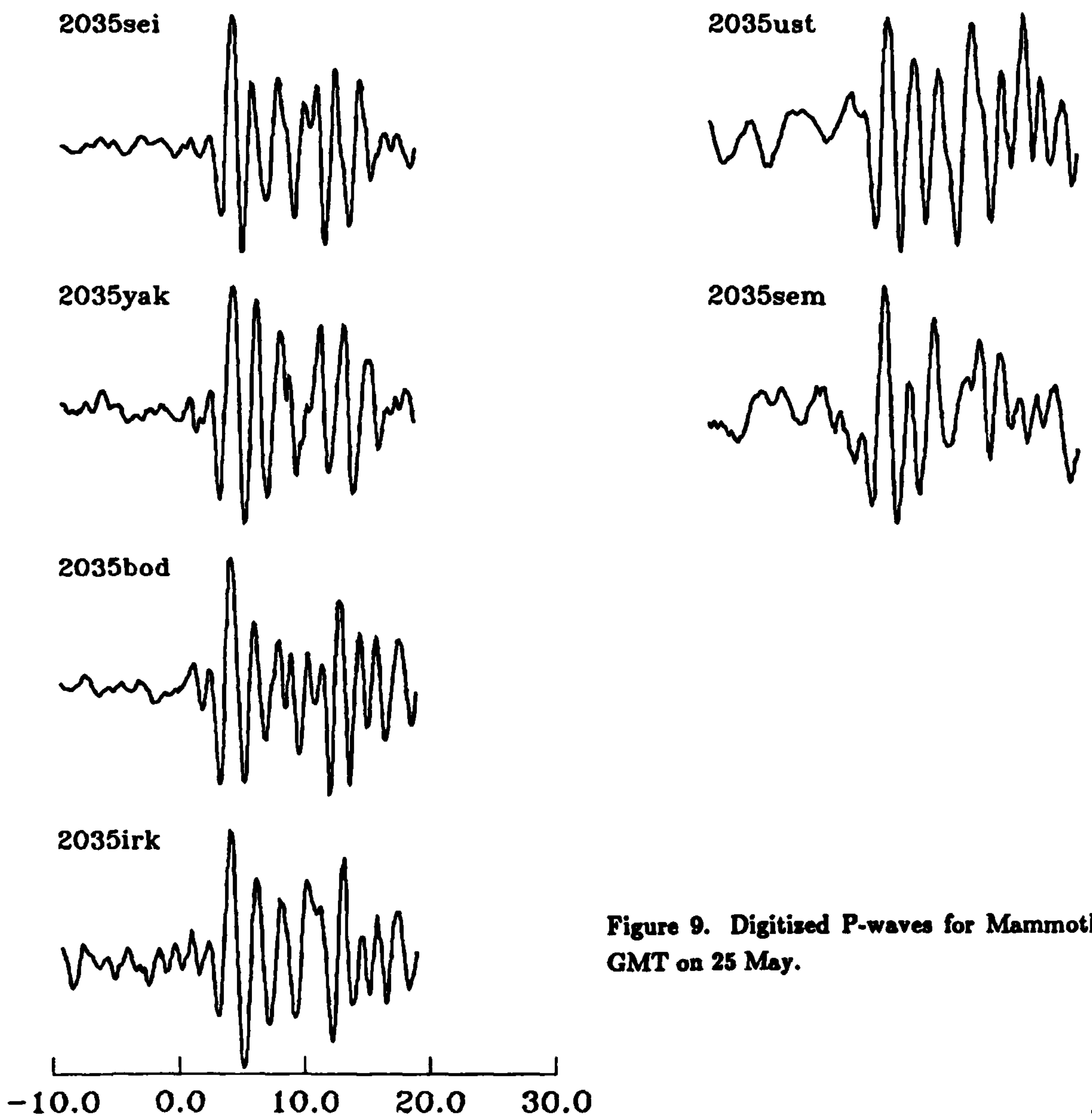

Figure 9. Digitized P-waves for Mammoth Lakes event at 20:35 GMT on 25 May.

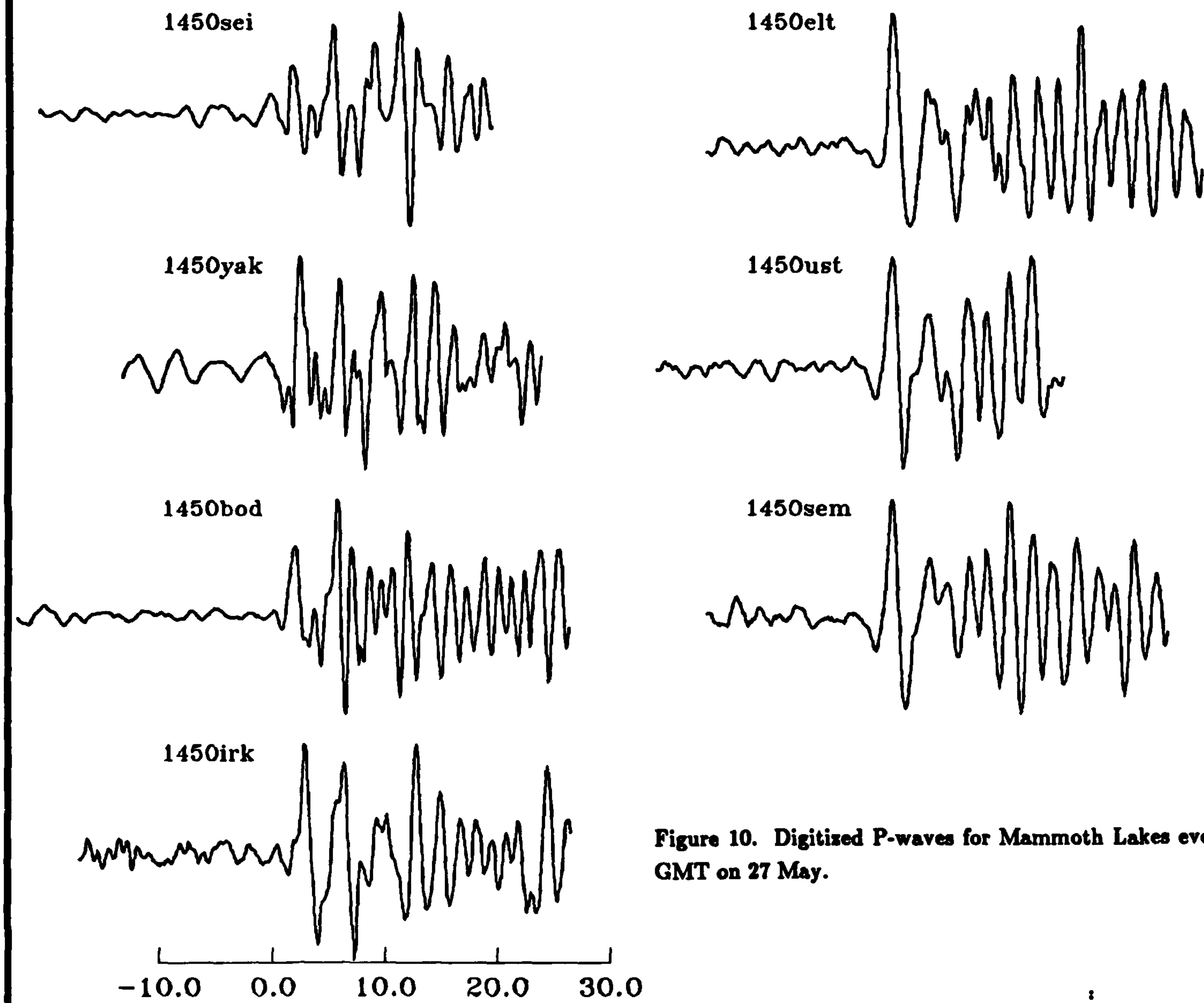

Figure 10. Digitized P-waves for Mammoth Lakes event at 14:50 GMT on 27 May.

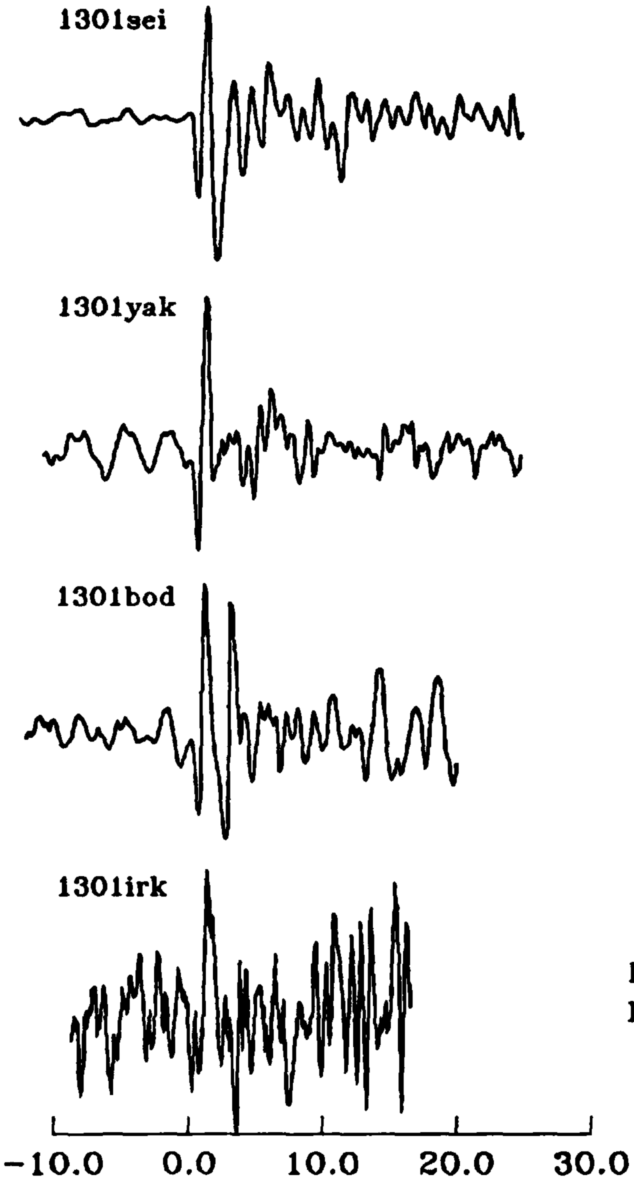

Figure 11. Digitized P-waves for Tonga event at 13:01 GMT on 27 May.

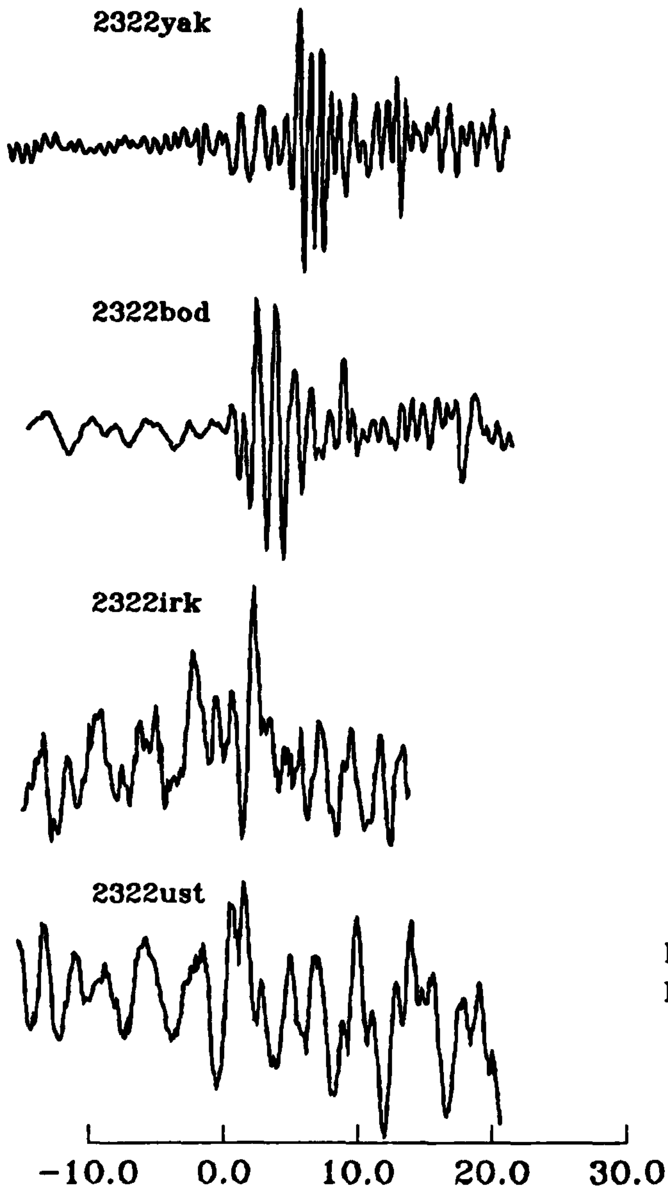

Figure 12. Digitized P-waves for Kurile event at 23:22 GMT on 25 May.

between maximum amplitude in the P-coda and amplitude of the P onset, we determined m_b for the Mammoth Lakes earthquakes from the maximum amplitude in the first two cycles and from the maximum amplitude in the first 12 seconds -- in both cases taken as one-half the peak-to-peak amplitude. The resulting individual and average m_b values are listed in Tables 8 and 9, together with magnitudes determined by the International Seismological Centre (ISC) and Moscow (MOS), and deviations δm_b from the ISC values.

A third set of magnitudes was determined from measurements of A and T on traces produced by deconvolving the instrument response from the digitized recordings. The deconvolution was accomplished using a program written by W. Peppin to calculate the complex transfer function of a seismograph, given the period and damping of the seismometer and galvanometer, together with the maximum magnification of the system and the period at which the maximum magnification occurs. The records were tapered and bandpass-filtered (0.25-8.0 Hz) before deconvolution, and filtered again (0.1-5.0 Hz bandpass) after deconvolution. Figures 13-17 show P-waves for all events except the Kurile earthquake, after correction for instrument response and filtering. For these records m_b was determined only using the maximum amplitude in the large phase following the initial P-wave. Magnitudes and residuals are listed in Table 10.

For the Tonga earthquake, values of m_b were determined from the maximum amplitude in the P-wave, from traces uncorrected and corrected for instrument response. Four of the stations for this event were beyond 100° and distance corrections were taken from a curve developed by Ringdal (1985).

Table 8. Magnitudes and Residuals, Uncorrrected Data, First Two Cycles

	05251633		05251944		05252035		05271450		Average
Sta	m_b	δm_b	m_b	δm_b	m_b	δm_b	m_b	δm_b	δm_b
BOD	5.47	-.63	4.97	-.63	4.96	-.34	5.34	-.36	-.49±.16
ELT*							5.78	+.08	+.08±.0
IRK	5.53	-.57	4.98	-.62	4.84	-.46	5.76	+.06	-.40±.31
KZL*	5.58	-.52							-.52±.0
SEI	5.67	-.43	5.17	-.43	5.09	-.21	5.54	-.16	-.31±.14
SEM	5.72	-.38	4.73	-.87	4.89	-.41	5.80	+.10	-.39±.40
UST	5.42	-.68	4.68	-.92	4.92	-.38	5.69	-.01	-.50±.39
YAK	6.16	+.06	5.21	-.39	5.48	+.18	6.38	+.68	+.13±.44
Avg	5.66		4.96		5.03		5.75		
ISC	6.1		5.6		5.3		5.7		
MOS	6.3		5.7		5.5		5.9		

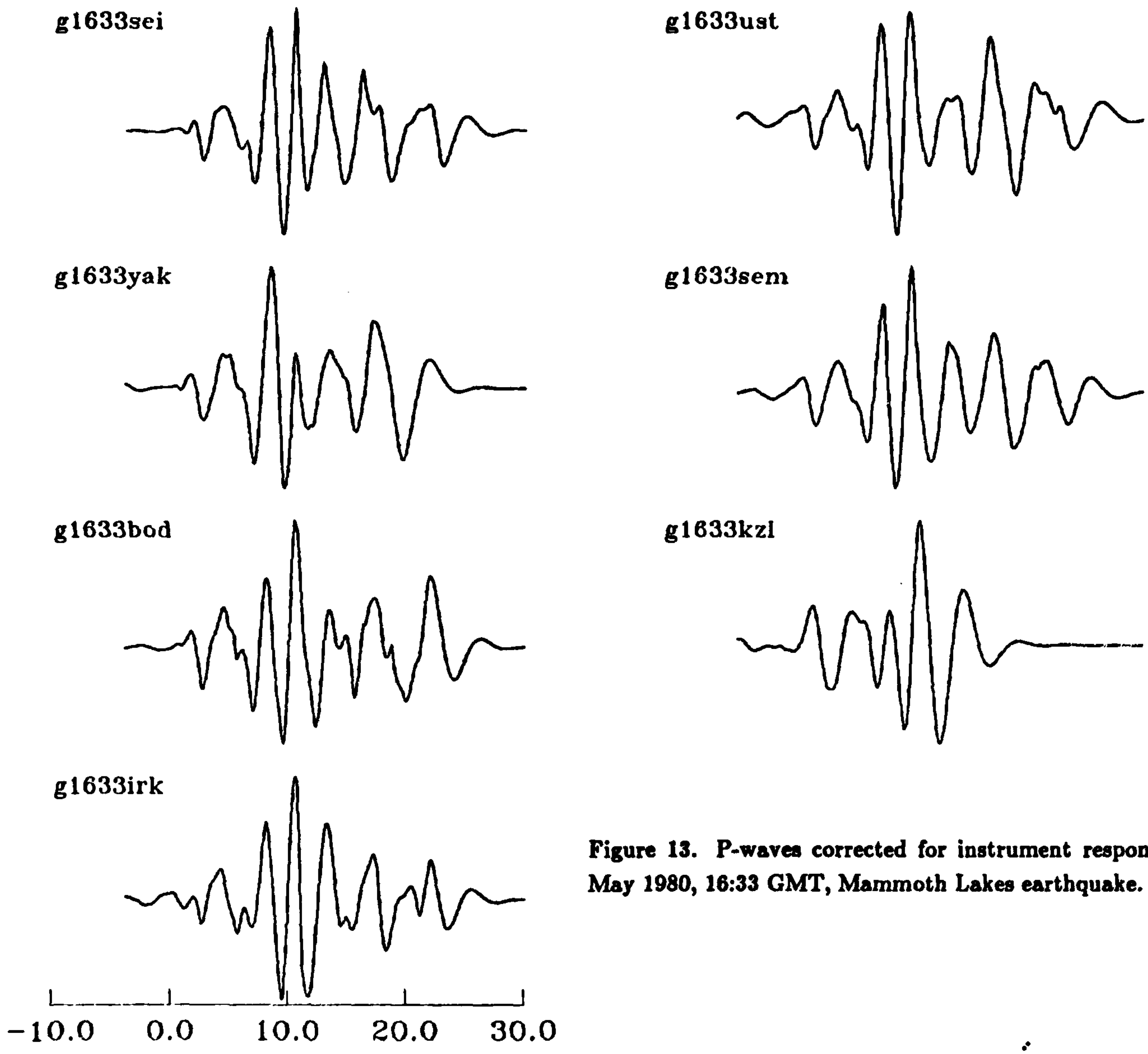

Figure 13. P-waves corrected for instrument response for the 25 May 1980, 16:33 GMT, Mammoth Lakes earthquake.

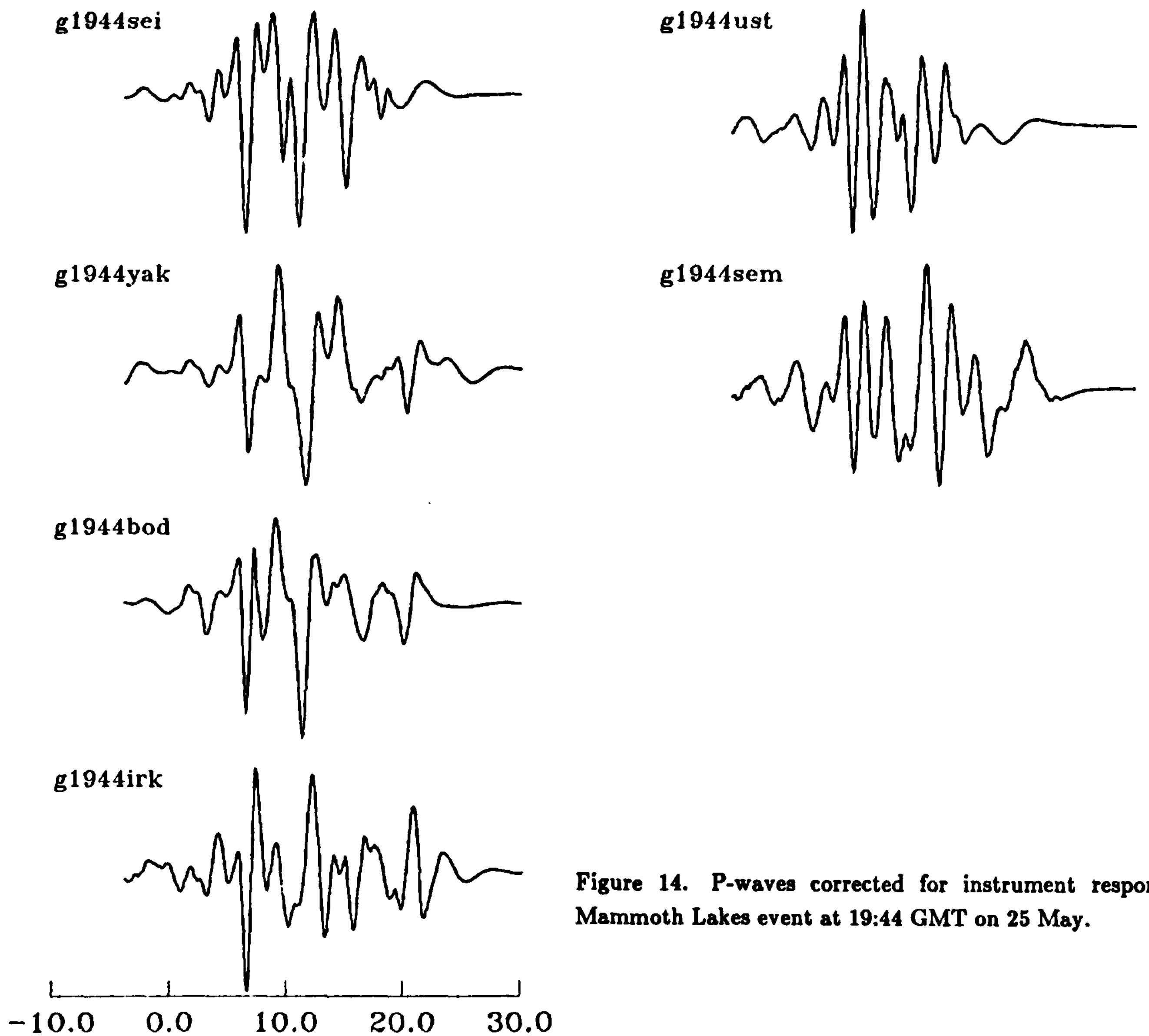

Figure 14. P-waves corrected for instrument response for the Mammoth Lakes event at 19:44 GMT on 25 May.

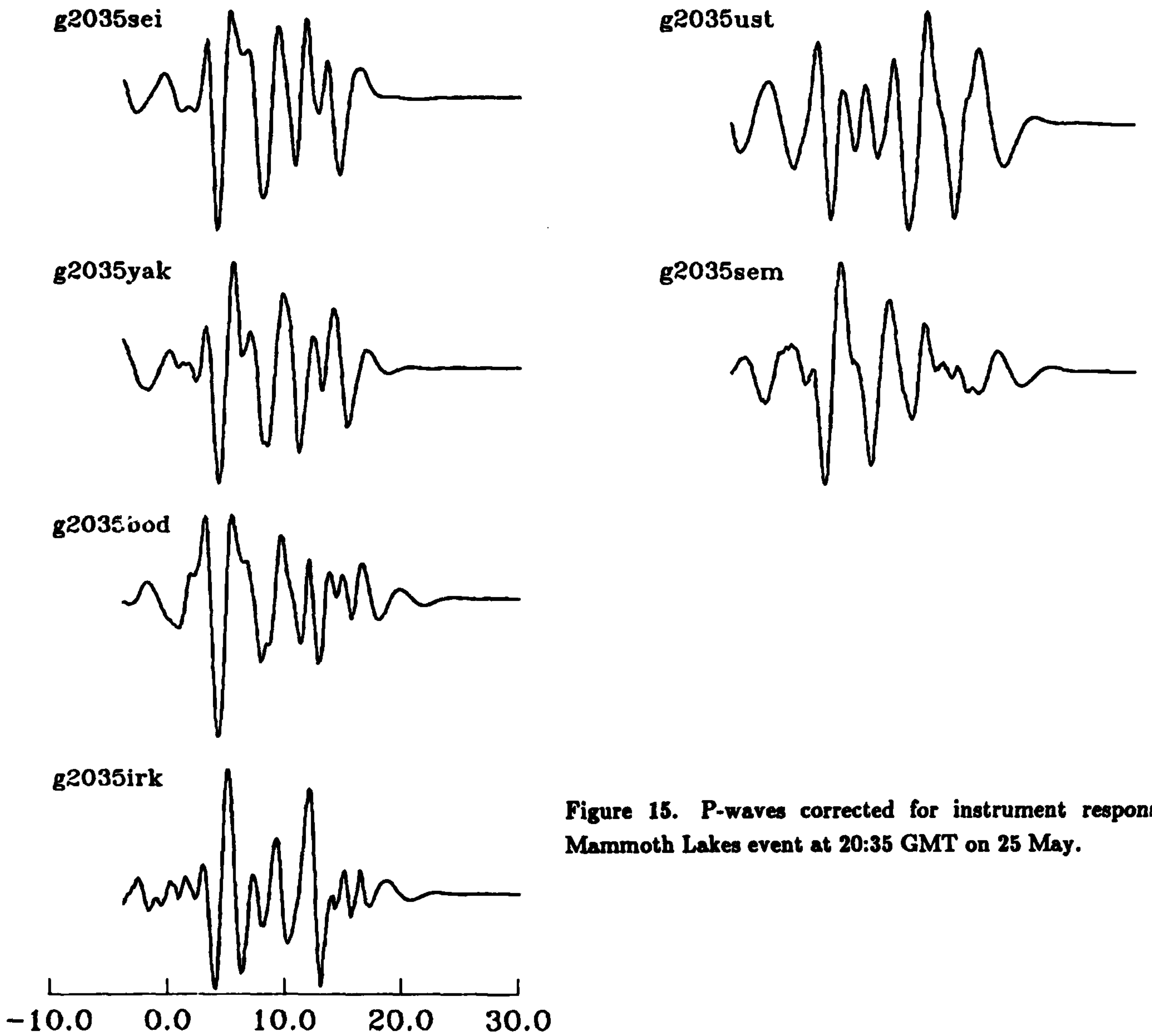

Figure 15. P-waves corrected for instrument response for the Mammoth Lakes event at 20:35 GMT on 25 May.

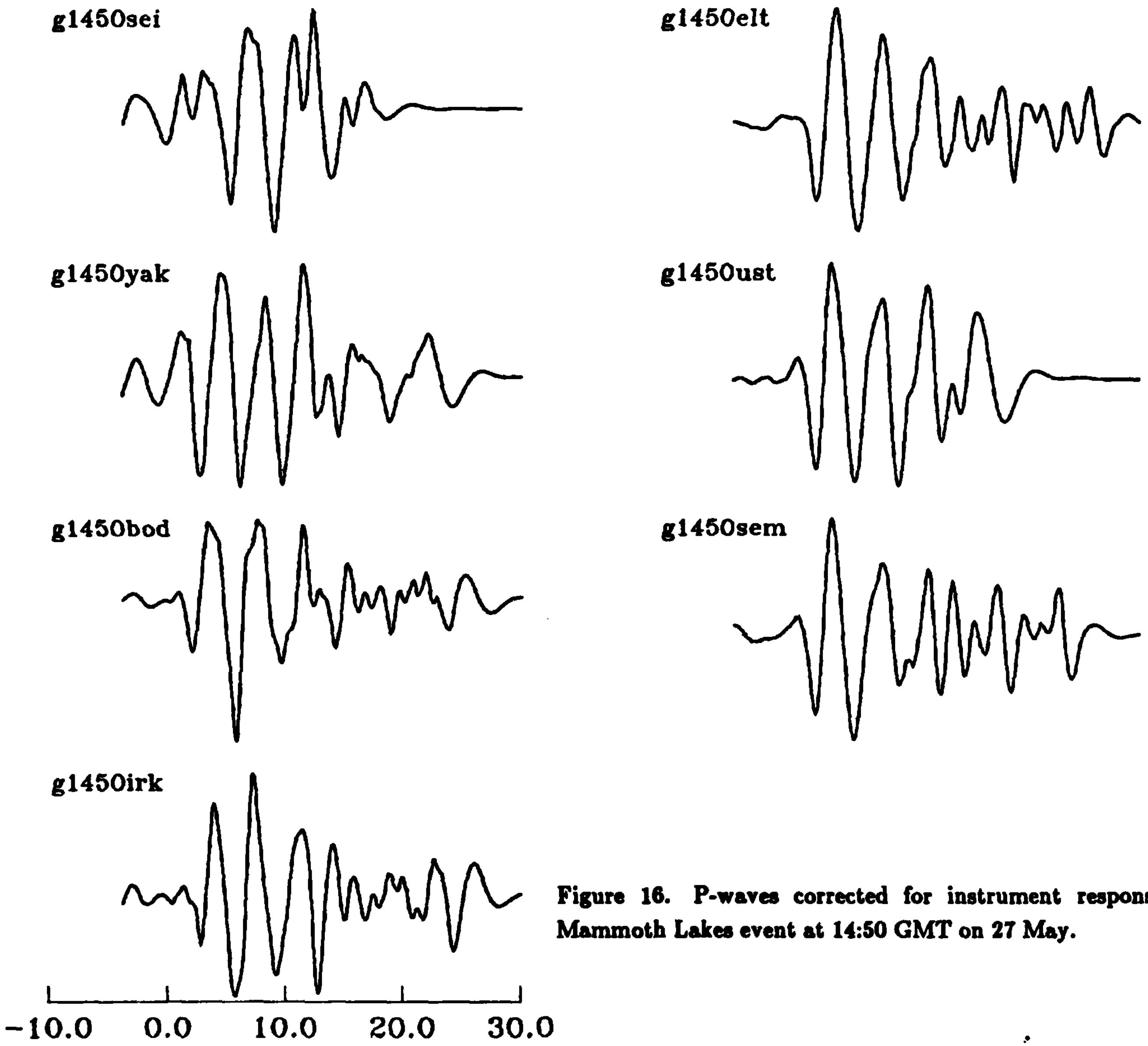

Figure 16. P-waves corrected for instrument response for the Mammoth Lakes event at 14:50 GMT on 27 May.

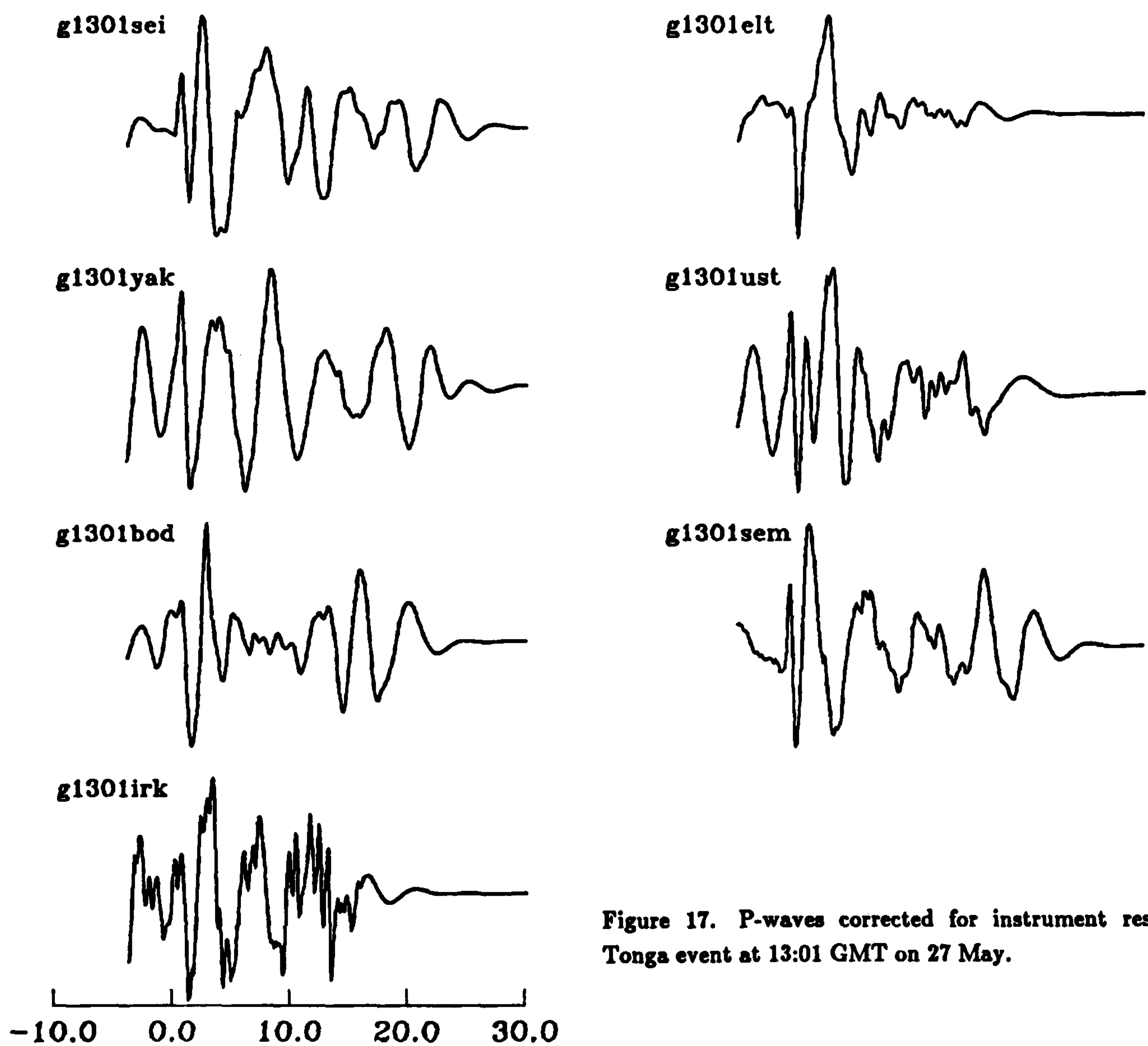

Figure 17. P-waves corrected for instrument response for the Tonga event at 13:01 GMT on 27 May.

Table 9. Magnitudes and Residuals, Uncorrrected Data, First 12 Seconds									
	05251633		05251944		05252035		05271450		Average
Sta	m_b	δm_b	m_b	δm_b	m_b	δm_b	m_b	δm_b	δm_b
BOD	6.04	-.06	5.76	+.16	5.46	+.16	5.66	-.04	+.06±.12
ELT*							5.59	-.11	-.31±.0
IRK	6.16	+.06	5.66	+.06	5.40	+.10	5.58	-.12	+.03±.10
KZL*	6.04	-.06							-.06±.0
SEI	6.48	+.38	5.81	+.21	5.62	+.32	6.03	+.33	+.31±.07
SEM	6.34	+.24	5.63	+.03	5.48	+.18	5.76	+.06	+.13±.10
UST	6.18	+.08	5.52	-.08	5.22	-.08	5.71	+.01	-.02±.08
YAK	6.60	+.50	6.10	+.50	5.90	+.60	6.04	+.34	+.49±.11
Avg	6.30		5.75		5.51		5.80		
ISC	6.1		5.6		5.3		5.7		
MOS	6.3		5.7		5.5		5.9		

Table 10. Magnitudes and Residuals, Corrrected Data, First 12 Seconds									
	05251633		05251944		05252035		05271450		Average
Sta	m_b	δm_b	m_b	δm_b	m_b	δm_b	m_b	δm_b	δm_b
BOD	6.12	+.02	5.65	+.05	5.50	+.20	5.70	+.00	+.07±.09
ELT*							5.77	+.07	+.07±.0
IRK	6.34	+.24	5.73	+.13	5.56	+.26	5.99	+.29	+.23±.07
KZL*	6.24	+.14							+.14±.0
SEI	6.47	+.37	5.98	+.38	5.76	+.46	6.00	+.30	+.38±.07
SEM	6.32	+.22	5.71	+.11	5.53	+.23	5.80	+.10	+.17±.07
UST	6.13	+.03	5.60	+.00	5.41	+.11	5.64	-.06	+.02±.07
YAK	6.74	+.64	6.22	+.62	6.10	+.80	6.35	+.65	+.68±.08
Avg	6.34		5.82		5.64		5.89		
ISC	6.1		5.6		5.3		5.7		
MOS	6.3		5.7		5.5		5.9		

* – ELT and KZL not used in determining average m_b values.

Table 11. Magnitudes and Residuals for Tonga Event				
	Uncorrected Data		Corrected Data	
Sta	m_b	δm_b	m_b	δm_b
BOD	5.58	-.42	5.83	-.17
ELT	6.09	+.09	6.22	+.22
IRK	5.38	-.62	5.66	-.34
SEI	6.19	+.19	6.17	+.17
SEM	6.07	+.07	6.06	+.06
UST	5.79	-.21	5.78	-.22
YAK	6.16	+.16	6.15	+.15
Avg	5.89		5.98	
ISC	6.0		6.0	
MOS	5.9		5.9	

Discussion

Magnitude m_b has been determined for five earthquakes on 25 and 27 May 1980, from recordings at eight Soviet seismic stations on a 4,300 km-long profile from eastern Kazakh to eastern Siberia. In general, magnitudes from this study for the Mammoth Lakes earthquakes (Tables 9 and 10) are about 0.2 m_b unit higher than those determined by the ISC, but for the Tonga event our m_b is close to the ISC value. Our values are about the same as magnitudes attributed to Moscow in the ISC *Bulletin*: For the data uncorrected for instrument response average values in this study differ from the Moscow m_b by 0.01±0.06 unit; for the corrected data our values are higher than those of Moscow by 0.07±0.06. Magnitudes determined from A and T measured in the first two cycles of the P-wave for the Mammoth Lakes earthquakes (Table 8) averaged 0.33 and 0.50 m_b unit smaller than the ISC and Moscow values, respectively.

The largest positive m_b residuals were for station YAK (average δm_b = +0.33 for the uncorrected data in Tables 9 and 11; +0.42 for the corrected data in Tables 10 and 11). Yakutsk is located on the central Siberian platform in an area where, according to Potap'ev *et al.* (1974), the depth to crystalline basement is shallow, 0.5-1.0 km. About 10 km west of Yakutsk a major north-south fault offsets basement rocks, with the western side downdropped by about 4 km. P-wave velocities in the crust are high, 6.2-6.4 km/sec (Vol'vovsky, 1973), the crust is about 40 km thick, and the P_n velocity is about 8.0 km/sec (Vol'vovsky and Vol'vovsky, 1975; Ryall *et al.*, 1980).

The largest negative m_b residuals were observed for station IRK for the Tonga event (-0.62 uncorrected, -0.34 corrected), for which the raypath crosses the southern part of the Baikal rift zone in a WNW direction. Station BOD, at the northeast end of the rift, also has negative residuals for the Tonga event (-0.31 uncorrected, -0.12 corrected). The rift

zone is characterized by complex geologic structure, including deep crustal inhomogeneities and velocity anomalies in areas of recent rifting. Within the rift zone P-wave velocity in the crust increases from 5.8 km/sec near the surface to 6.4 km/sec at the crust/mantle interface, crustal thickness is 34-36 km, and P_n velocity is 7.7-7.8 km/sec (Puzyrev *et al.*, 1975; Ryall *et al.*, 1980). Puzyrev *et al.* (1977) attribute the low P_n velocity to partial melting of upper mantle material, and compare the Baikal region with the East African rift system, the Rhine graben and the Basin and Range province. It is interesting that IRK and BOD, located on the southern edge of the central Siberian platform just north of the Baikal rift, both have positive values of δm_b (+0.03±0.10 and +0.06±0.12 uncorrected, respectively; +0.23±0.07 and +0.07±0.09 corrected) for the Mammoth Lakes earthquakes, for which the P-waves approach the stations in a SSW direction across the platform and do not appear to be affected by the structure of the rift zone. According to Puzyrev *et al.* (1977) the platform is characterized by uniform layering, with distinct reflecting horizons at depths of 18-21 and 23-27 km, crustal thickness of about 40 km, and "normal" P_n velocity of about 8.1 km/sec.

The m_b residuals for station SEM are intermediate between IRK and YAK. SEM is near the Irtysh River, on the boundary between the west Siberian platform to the north and the Kazakh fold system to the south. In this area the crustal thickness is about 45 km, P_n velocity is 8.2-8.4 km/sec, and P-velocity in the crust is high (Vol'vovsky and Vol'vovsky, 1975). The station is in the Zaysan fold belt, which is relatively simple in terms of stratigraphy and structure. Sediments, principally of Carboniferous age, contain thick limestone deposits and lesser amounts of interbedded volcanics. Folding and faulting are relatively minor in this area, compared with more extensive folding, faulting and intrusion in the Chingiz-Tarbagatai geanticlinal zone to the southwest, in which the eastern Kazakh test site is located (Peyve and Mossakovsky, 1982). For the Mammoth Lakes earthquakes δm_b for this station is +0.13±0.10 for the uncorrected data (Table 9) and +0.17±0.07 for the corrected data (Table 10). For the Tonga earthquake it is +0.07 for the uncorrected, +0.06 for the corrected data. As noted above, the Soviet stations are near a maximum on the radiation pattern for the Mammoth Lakes earthquakes, and near the null axis for the Tonga event.

Several published works treat magnitude residuals for stations of the Soviet network, and provide the basis for a comparison with our results (Table 12). First, in a study of magnitude and global network detection capability Ringdal (1985) recomputed m_b for about 70,000 earthquakes, using A and T values given in the ISC *Bulletin* and a maximum-likelihood estimation technique (Ringdal, 1976). In another study, North (1976) calculated mean station magnitude bias from m_b values given in the ISC *Bulletin* for nearly 40,000 events from 1964 to 1973. The biases were computed for the "best" (in terms of events reported) 72 stations with respect to the mean magnitude of observations reported by this set of stations, with the requirement that an event be reported by more

than 15 of these stations before a bias was calculated.

In work by Soviet authors Vanek *et al.* (1978, 1980) determined magnitude *corrections* (Δm_b) for 32 reference stations of the Unified System of Seismic Observations (ESSN) of the Soviet Union, following a recommendation of the KAPG Conference at Prague in 1972 to create a uniform system for determining magnitude for the Eurasian continent. The station corrections were determined separately for phases PV, PV_S and PH -- respectively the P-wave recorded on vertical mid-band, vertical short-period and horizontal mid-band seismographs. Calculations were also made separately for five different source regions around the USSR -- Alaska, Japan, the Phillipines, Asia and the Mediterranean. The number of earthquakes in each source region was not given in the 1980 paper, but in the earlier work it ranged from 35 events for Asia and the Mediterranean to 93 events for Japan. The corrections were with respect to one of the reference stations, OBN, selected at least in part for its bias toward large m_b values. Based on a comparison of Δm_b values for the various source regions the reference stations are grouped according to the number of corrections needed for the different source regions. Thus, a station for which Δm_b was the same for all five source regions was classed as a reference station of the *I Kind*, a station with the same correction for four of the five source regions would be a station of the *II Kind, etc.* Of interest to our study, station SEM has the same PV_S correction for all of the source regions, $\Delta m_b = +0.32$, making it a station of the *I Kind* and indicating that it has a δm_b *bias* of -0.32 relative to station OBN. Standard deviations are not given by Vanek *et al.* (1980) but in the earlier work they average ± 0.05 m_b unit. For comparison with magnitude bias given by other authors, we reversed the sign of Δm_b and increased all of the resulting values by 0.39 -- Ringdal's (1985) bias for station OBN, which Vanek *et al.* use as a base station.

With a couple of exceptions the station residuals listed in Table 12 from the work of Ringdal (1985), North (1976) and Vanek *et al.* (1978, 1980) agree to within a few hundredths of a unit of m_b. Our station residuals are based on a very limited data set and show more scatter when compared to those of the other authors. However, they are in general agreement with the published values, and two of the stations -- SEM and YAK have values of δm_b that are in excellent agreement with those of Vanek *et al.* and Ringdal, respectively.

As a final step we computed the m_b bias between a granite site at the Nevada Test Site and the Soviet stations listed in Table 12. In this calculation we used A and T measurements listed by Der *et al.* (1978) for 83 seismic events for the period September 1976 to March 1977, recorded by a digital seismic system (SDCS) at station OB2-NV (Climax stock at north end of Yucca Valley on NTS). In the Der *et al.* report, the A values are peak-to-peak amplitudes in nanometers, and magnitudes are computed using distance corrections of Veith and Clawson (1972). For consistency with the work by Ringdal (1985) and North (1976), magnitudes were recomputed using the Gutenberg and Richter

Table 12. Comparison of Station Residuals and δm_b(OB2-NV)						
Sta	*Ringdal*	*North*	*Vanek*[1]	δm_b[2]	δm_b[3]	$\delta m_b(OB2-NV)$[4]
BKR	+0.38±0.33		+0.30			-0.44
BOD	-0.02±0.34			-0.05	+0.10	-0.11
CLL	+0.16±0.26	+0.20±0.32	+0.09			-0.25
ELT	+0.15±0.34			-0.01	+0.15	-0.20
FRU	+0.35±0.33		+0.36			-0.46
ILT	+0.08±0.32		+0.03			-0.16
IRK	-0.03±0.31			-0.32	-0.06	-0.04
KHC	+0.03±0.26	+0.10±0.26	+0.08			-0.17
KHE	+0.37±0.31		+0.31			-0.44
KRA	+0.32±0.29	+0.22±0.29	+0.22			-0.35
KZL				-0.06	+0.14	-0.14
MOX	+0.07±0.25	+0.02±0.27	+0.01			-0.13
OBN	+0.39±0.33		+0.39			-0.49
PET	+0.24±0.36		+0.35			-0.40
PRU		+0.04±0.24	-0.06			-0.09
SEI				+0.25	+0.28	-0.37
SEM			+0.07	+0.10	+0.12	-0.20
TIK	+0.03±0.37		+0.00			-0.12
UST				-0.12	-0.10	+0.01
YAK	+0.43±0.34			+0.33	+0.42	-0.49
YSS	+0.20±0.41		+0.02			-0.21
ZAK	-0.11±0.33		-0.03			-0.02

1 -- Given by authors as Δm_b corrections relative to base station OBN. Sign reversed and all values increased by 0.39 for comparison with Ringdal (1985).
2 -- Mean of δm_b for Tonga earthquake plus average δm_b for four Mammoth Lakes events from Table 9. Uncorrected data.
3 -- Mean of δm_b for Tonga earthquake plus average δm_b for four Mammoth Lakes events from Table 10. Corrected data.
4 -- Average residual (-0.10±0.35) for OB2-NV with respect to ISC *Bulletin* minus average station residual.

(1956) corrections and dividing the peak-to-peak amplitudes by two to obtain zero-to-peak amplitudes. Residuals for the 83 events were calculated as $\delta m_b = m_b(OB2-NV) - m_b(ISC)$, and these were averaged to obtain an average δm_b of

-0.09±0.39. Five values that fell outside the 2σ limits ($-0.87 \leqslant \delta m_b \leqslant 0.69$) were dropped and the average δm_b recalculated to obtain -0.10±0.35. This number represents the average bias of the OB2-NV site with respect to network-averaged m_b values listed in the ISC *Bulletin*. To determine the bias of OB2-NV with respect to the Soviet stations, the average residuals in Table 10 for those stations were subtracted from -0.10. The resulting bias values are listed in the right-hand column of Table 12.

Of particular interest to questions of yield verification, the m_b bias of the NTS granite site with respect to station SEM at Semipalatinsk is -0.20, with a range of -0.17 to -0.22. The smaller of these figures (-0.17) is based on the study by Vanek *et al.* (1980), and the larger (-0.20, -0.22) are from our measurements of Soviet records of the Mammoth Lakes and Tonga earthquakes. The reader should be reminded that the Semipalatinsk station is about 100 km from the East Kazakh test site, and that, according to Peyve and Mossakovsky (1982), crustal rocks under the test site have been subjected to greater folding, faulting and intrusion than those under the seismic station.

It should also be noted that the bias values in Table 12 represent only the bias due to attenuation in the upper mantle and crust under the respective seismic stations; they do not include other effects such as differences in coupling for explosions at the two test sites, effects due to tectonic release, or those related to focusing and defocusing of seismic waves in the vicinity of a given explosion. It is also possible that magnitude determinations in this study were biased because of the different passbands of the instruments used at different stations. In an early study (SIPRI, 1968) Whitham reported that intermediate-band instruments in Canada gave magnitudes that averaged about 0.3 m_b larger than short-period instruments; in the same report Karnik reported that magnitudes based on broadband Kirnos recordings were 0.5 m_b greater than for a Western narrowband instrument, but the difference was only 0.2-0.3 m_b if a short-period SVK-M instrument was used. In an extension of this study we plan to convolve the ground motion illustrated in Figures 13-17 with the SDCS instrument response, for a better comparison with the magnitudes determined from data collected at NTS.

Acknowledgement

Andy Jurkevics checked some of the calculations in this study and found an error in the galvanometer damping constant for one of the stations. William A. Peppin wrote a computer program to remove the Kirnos instrument response from the seismic data. Most of this research was done while the author was a visiting scientist at the Center for Seismic Studies, supported by the Defense Advanced Research Projects Agency under Contract MDA-903-84-C-0020, monitored by the Defense Supply Service-Washington; part of the work was done at the University of Nevada, supported by the Defense Advanced Research Projects Agency under contract number F49620-83-C-0012, monitored by the Air Force Office of Scientific Research.

APPENDIX A

Description of the SKM-3 System and Determination of Response Characteristics for the Data Used in this Study

According to Aranovich *et al.* (1974), "systems of [the SKM-3] type are used primarily for the recording of body waves, generated by earthquakes of medium intensity ($3 \leqslant M \leqslant 5-6$) at relatively large epicentral distances (greater than 1,000 km). For this it is necessary to have magnification of the order of 30,000-100,000 for periods of ground motion in the range 0.3-1.5 seconds. Further increasing the magnification or broadening the frequency response to longer period is impossible without special filtering, because of microseisms of the first type and other seismic noise. The high gains mentioned above can be achieved only at stations located in especially favorable surface conditions and sufficiently distant from sources of interference. Instrument constants and gain level are a function of the noise level at each site. To reduce the influence of local seismic noise four standard types of amplitude response are used. The instrument constants m, p, q, s and U_{max} (where U_{max} is the maximum value of the frequency response) corresponding to the four types of response are given in Table A1. The corresponding amplitude response curves are shown on Figure A1."

The standard SKM-3 seismograph system consists of two SGKM-3 (horizontal) and one SVKM-3 (vertical) seismometers, three GK-VIIM galvanometers and a PS-3M drum recorder. The latter registers the light beams from the three galvanometers on a 29-cm wide by 90-cm long photographic recording. Time marks from a chronometer are printed once per minute. Drum speed was 60 mm/minute for all of the SKM-3 stations used in this study except KZL, which had drum speed of 120 mm/minute.

In general, for a seismometer-galvanometer system, the relative amplitude response U at period T is given by (Archangel'skii *et al.*, 1974)

Table A1. Instrument Constants for SKM-3 Seismic Systems

Type	m	p	q	s U_{max}	
I	2.50	4.85	3.47	1.93	1.67
II	11.65	19.85	20.62	8.57	1.23
III	2.77	4.12	1.95	0.86	1.28
IV	10.62	12.88	7.82	2.44	1.11

$$U(T) = \frac{1}{(T^{-2} + a + bT^2 + cT^4 + dT^6)^{1/2}} , \tag{1}$$

where

$$a = m^2 - 2p ,$$

$$b = p^2 - 2mq + 2s ,$$

$$c = q^2 - 2ps ,$$

$$d = s^2 ,$$

$$m = 2\left(\frac{D_s}{T_s} + \frac{D_g}{T_g} \right) ,$$

$$p = \frac{1}{T_s^2} + \frac{1}{T_g^2} + \frac{4D_sD_g}{T_sT_g}(1 - \sigma^2) ,$$

$$q = 2\left(\frac{D_s}{T_sT_g^2} + \frac{D_g}{T_gT_s^2} \right) ,$$

$$s = \frac{1}{T_s^2}\frac{1}{T_g^2} .$$

where T and D are the period and damping factor, respectively, subscripts s and g refer to the seismometer and galvanometer, and σ^2 is the coupling coefficient.

The total gain of the system is given by

$$V(T) = \frac{2AU}{L}\left(\frac{4K_sD_sD_g\sigma^2}{K_gT_sT_g} \right)^{1/2} , \tag{3}$$

where A is the optical lever, L is the length of the pendulum, K_s and K_g are the moments of inertia of the seismometer and galvanometer, and the other parameters are as given above.

The phase shift at period T is given by

$$\tan \gamma = \frac{-1 + pT^2 - sT^4}{mT - qT^3} . \quad (4)$$

Depending on the period T the phase shift may vary from $-\frac{\pi}{2}$ (for T = 0) to $\frac{3\pi}{2}$ (for T = ∞).

Table A2 lists the seismometer and galvanometer constants used to calculate response curves (Figure 6, above) for the instruments used in this study, from equations (1) and (2). For stations BOD, IRK and SEM the constants were taken from Shishkevish (1974) and the response curves were checked to insure that the range of T_m was the same as indicated on the recordings or in the Soviet bulletins. For station ELT the constants given by Shishkevish were modified to give the appropriate upper limit of T_m, and the same constants were used for UST. For station YAK Shishkevish lists instrument parameters only for the horizontal-component seismographs, and these give a different range of T_m than that on the records. For KZL and SEI Shishkevish does not list instrument constants. As a result, for KZL, SEI and YAK various combinations of instrument constants were tried, based primarily on tables of standard setups given by Shishkevish and by Aranovich *et al.*, until response curves matched the range of T_m marked on the records.

Table A2. Instrument Parameters for Data in this Study

Station	T_s	D_s	T_g	D_g	σ^2
BOD	1.74	0.53	0.37	1.84	0.160
ELT	2.2	0.5	0.37	1.6	0.25
IRK	1.8	0.5	1.4	.5	0.025
KZL	1.7	0.5	0.25	2.5	0.25
SEI	1.74	0.53	0.37	1.84	0.154
SEM	2.0	0.8	1.2	.8	0.13
UST	2.2	0.5	0.37	1.6	0.25
YAK	1.7	0.5	0.4	1.8	0.15

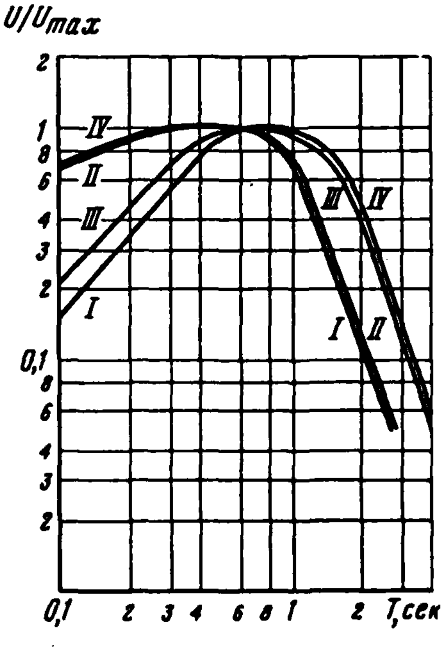

Figure A1. Standard amplitude response curves for SKM-3 system (Aranovich, *et al.*, 1974).

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